

Presented at the 5th Symposium on Theory and Practice of Robots and Manipulators
1984, Udine, Italy, sponsored by CISM-IFTOMM.

THE BRACING STRATEGY FOR ROBOT OPERATION¹

Wayne J. Book, Sanh Le, and Viboon Sangveraphunsiri
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332
U.S.A.

Summary

A new strategy of robot operation, the bracing strategy, is presented. Under this strategy an arm is moved into position then rigidized by bracing against either the work piece or an auxiliary, static structure. Subsequent precision motion does not involve the entire arm, but only degrees of freedom at the end of the arm. The advantage of this strategy is that it allows high speed, precision motion with a light weight, flexible arm. Light arms require smaller actuators, less energy, may be faster, are safer, and are less expensive.

Four means of clamping to the structure are considered: A simple normal force, mechanical clamping, vacuum attachment, and magnetic attachment. Each means has restrictions and advantages. Arm control with the bracing strategy requires four modes: gross motion control, rendezvous with the bracing structure, control of gross actuators after bracing and control of fine motion actuators distal to the bracing point.

1. This work is partially supported by the National Science Foundation of the U.S.A., Grant No. MEA-8303539

The Rationale for a Bracing Strategy

Ultimately, one must have fast motion to have the highest performance for a robot arm. Most robot tasks consist of gross motion and fine motion phases. Gross motion involves large movements with a relatively predictable destination enabling trajectory planning. These motions require a high force to inertia ratio for rapid completion. Fine motion involves smaller, more precise movements which are less predictable. They could arise from sensory or joint angle feedback in response to disturbances, statistical variation in dimensions, or changes in the environment. To accomplish these motions quickly a high bandwidth servo system is required. Such bandwidth typically requires rigidity in the actuated structure, hence additional structural mass. The traditional approach accomplishes both gross and fine motions with the same actuators and linkage. Thus the structural mass required for the fine motion speed detracts from the gross motion speed.

The research underway seeks to eliminate the conflict between gross and fine motion speed. The configurations studied effectively reduce the distance from the end point to a "fixed" base during the fine motion phase by "bracing" it against a static structure or the work piece itself. This approach is especially relevant to long arms with light payloads as documented by the author previously¹. This is analogous to the strategy of human workers who steady their hand for precise work by bracing their arm against a work bench. It is also a variation of the strategy of extending the range of an arm by providing it with mobility. For mobile robots the strategy is typically to transport the arm to the vicinity of the work piece, deactivate the mobility subsystem, and activate the arm. Both cases are examples of allocation of the motion responsibilities to the most appropriate degrees of freedom. Similar approaches have been proposed by Hogan² and applied specifically to drilling.

The advantages and disadvantages of bracing compared to other strategies for using lightweight arms are being considered. Particular consideration is given to the mechanical design and joint control consequences of employing this strategy as opposed to conventional rigid arm strategies. The increased control complexity, additional degrees of freedom, and end point location issues penalize the bracing strategy.

Alternative Means of Bracing

For a bracing mechanism design, the following parameters are evaluated for comparison purposes: holding force/unit weight, size, required working environment, power consumption, reliability, maintenance.

In all cases the controllable force for clamping is applied normal to the surface of the bracing structure. Consequently, the coefficient of friction between the robot and structure is an important parameter.

Simple Normal Force

The most simple and least reliable means of bracing for robots is the one used extensively by humans. By simply applying a normal force to the bracing structure as shown in Fig. 1, rigidization can be achieved. Unlike the other methods, a net force is imparted to the bracing structure which may be unacceptable. Since the joint actuators would apply this force, a means of force control would be necessary in addition to position and/or velocity control. A continuous actuation would mean substantial energy consumption. Brakes or other means of locking the joints would circumvent this consumption. As observed in the human, an appropriate design can be effective and require low levels of actuation or rely totally on gravity. The mobile robot typically relies on gravity to achieve bracing. This method can also be used to supplement other bracing means. The only additional mechanical design consideration is to provide an durable, high friction surface for contact with the bracing surface.

Mechanical Clamping Device

This type of device requires edges, holes, or other features of a bench or work piece for attachment. The general design force/weight ratio is limited by the strain/stress relation of the material. Commercially available clamping devices achieve a force to weight ratio of up to 1000. This estimate does not include the weight of the actuating solenoid or hydraulic cylinder. The latter may dominate the total system weight and may reduce the ratio by one-half. Hydraulic, pneumatic, or electromagnetic actuation devices may be employed. A hydraulic ram may be used directly as in Fig. 2 with quite favorable size and weight advantages. Pneumatic and electromechanical actuation would likely require some type of mechanical linkage to provide mechanical advantage.

The energy consumption of the hydraulic clamping device is proportional to the stroke and area of the piston. Additional energy is consumed by the valving. If hydraulic actuators are used in the joints of the arm, the additional cost of hydraulic clamping will be greatly reduced. Simple on-off control of the clamping actuator will produce fast clamping with but

with high impacts on the work piece and high pressure transients. A more complex control circuit will be necessary to produce fast clamping without these adverse effects.

One obvious limitation of mechanical clamping is that the point of clamping must be near an edge so that opposing forces can be applied. A practical limitation on the range of separation of the opposing surfaces (thickness) for fast bracing exists. Positioning the arm to engage the clamping mechanism requires more complex maneuvers in the gross motion.

Vacuum Attachment

By providing suction to a cup with a pliable rubber-like material on its lip, a normal bracing force can be achieved as shown in Fig. 3. Suction will provide a normal force to the bracing surface limited by the atmospheric pressure around the arm and the area to which a vacuum is applied. Consequently, it is appropriate only where fairly large, smooth surfaces are available. The weight of such a system is derived from its mechanical structure and the vacuum fixtures such as connecting hoses and the cup. Thus, based on strength its force/weight ratio will be on the same order of the mechanical clamping devices. Because of the limit on negative pressure the force is proportional to area. The resulting large size may dictate that stiffness of the bracing point be increased by adding material to the cup. The energy consumption will depend on the strategy of controlling the air flow. Consequently the bulk and mass is expected to be larger than for mechanical clamping.

Permanent Magnets

Magnetic forces can be used to attach to ferrous clamping structures. Because of the constant current requirements for electromagnets, they have not been considered for providing the normal force directly. The permanent magnet is popular in temporary holding applications. A strong holding force is provided once good contact is established with the working surface. The force is strongly dependent on the gap between the magnet and the working surface. In general a permanent magnet circuit is designed with pole pieces to concentrate the flux density in the gap so as to increase the holding force as in Fig. 4. With a rare earth magnet a force to weight ratio of about 200 can be achieved in a small volume (5 cm³ for 900 N.). For a given geometry, the magnetic holding force is proportional to K^2 where K is the scale factor of the geometry.

There are basically two methods for releasing a work piece: flux diversion and depolarization. In flux diversion, an alternative return

path is connected to the magnetic circuit to divert flux going through the work piece, thereby releasing it from the magnet. This diversion may be actuated by a separate actuator or by the arm motion. In depolarization, a high impulse of unidirectional current is passed through the pole pieces to temporarily reverse the polarity of the poles and thus disrupt the flow path of the magnetic circuit and allow release. For a 2.5 cm diameter SeCo_5 rare earth magnet, a 10 ms pulse of 100' amp current is required for depolarization. This is a substantial complication to the method but one that is being explored.

Comparison of Bracing Means

All the candidate bracing means have advantages which could dominate in certain applications. Table 1 summarizes the characteristics which have been largely discussed above.

Table 1. Summary of clamping designs producing a holding force (normal) of 900 N.

| Characteristic | Magnet | Vacuum | Mechanical |
|--------------------|-----------------|----------------|----------------------|
| Material | SeCo_5 | metal + rubber | steel |
| Work environment | surface ferrous | surface smooth | edge or hole |
| Size (cm) | 3x2.5x1.3 | (10 dia) | 2.5 dia or less |
| Force/weight | 200 | 500 | 500 |
| Action (speed) | good | fair | excellent |
| Energy consumption | low | moderate | moderate |
| Maintenance | low | moderate | high |
| Reliability | excellent | good | good |
| Other | compact | noisy bulky | difficult rendezvous |

Control Issues in Bracing

To implement the bracing strategy several control issues must be addressed:

1. Gross motion control of a lightweight arm.

2. Rendezvous of the bracing mechanism with the bracing structure.
3. Control of the actuators between the base and the bracing point after bracing.
4. Control of the actuators distal to the bracing point after bracing.

It should also be clarified that the ability to successfully perform the first two tasks above does not constitute the ability to successfully manipulate with a flexible arm. The accuracy needed to rendezvous can be made less than required for the final manipulation task. Certainly the speed of manipulation after bracing can be made higher. Perhaps most importantly, the effect of disturbances on the braced arm are not as troublesome as for the unbraced arm.

Issues one and two above are quite challenging and have been treated by Truckenbrot³, Book¹ and others. The two may be treated together or separately, but separate treatment may allow for a robust treatment of errors and uncertainty in rendezvous while maintaining high speed gross motions.

After bracing has begun the arm is no longer an open loop kinematic chain and dynamics of the links between the base and the point of bracing are quite different than before bracing. If clamping prevents all translation and rotation the joints may move only by deforming the structure. If only some translations or rotations are restricted the arm has become a closed loop mechanism. The remaining degrees of freedom are available for positioning the end effectors. A force control mode is envisioned for the actuators in this case, and application of a downward force to enhance the clamping action will be helpful.

The control of distal joints after bracing contends with dynamics similar to conventional manipulation. The short links are essentially rigid. The exact position of the end effector may be poorly known based on the joint angles alone. A decreased emphasis on this source of information and increased reliance on direct measurements of the end point, either absolute or relative to the work piece is appropriate.

Ongoing Work

Research underway is constructing alternative bracing mechanisms and simple light weight arms and devising control algorithms. This will allow

practical evaluation of the bracing strategy.

1. Book, W.J. and M. Majette, "Controller Design for Flexible Distributed Parameter Mechanical Arms Via Combined State Space and Frequency Domain Techniques," to appear in J. Dynamic Systems, Measurement, and Control

2. Moore, S.R. and N. Hogan, "Part Referenced Manipulation--A Strategy Applied to Robotic Drilling," in Control of Manufacturing Processes and Robotic Systems, D. Hardt and W.J. Book, eds. American Society of Mechanical Engineers, New York, pp. 183-191, 1983.

3. Truckenbrot, A., "Modelling and Control of Flexible Manipulator Structures," Proc. of the Symposium on the Theory of Robots and Manipulators, September, 1981, Zabrow, Poland.

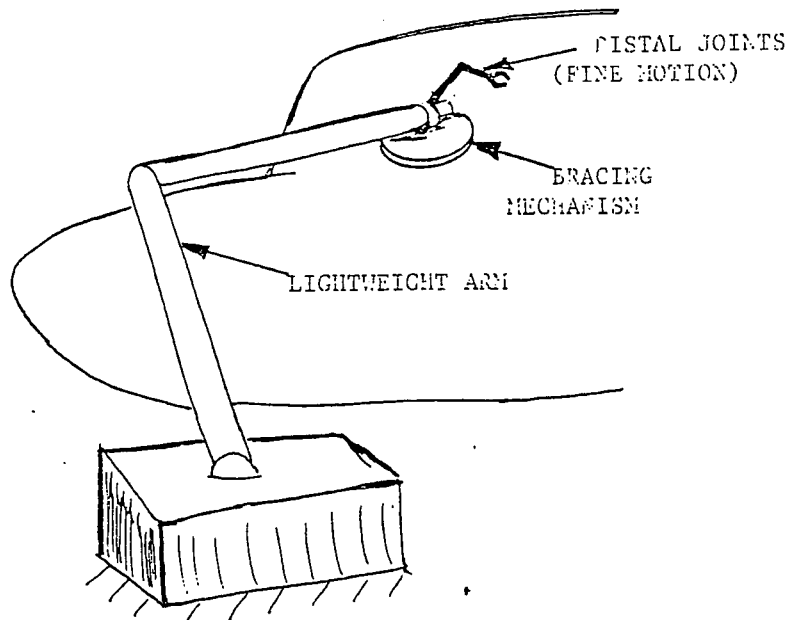


Fig. 1 The Bracing Strategy

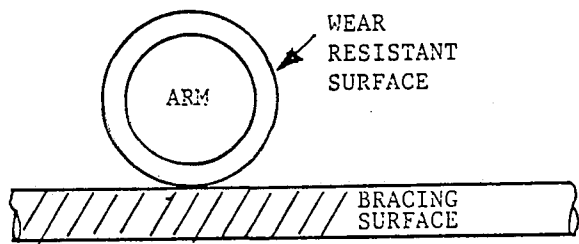


Fig. 2 Simple Normal Force for Bracing

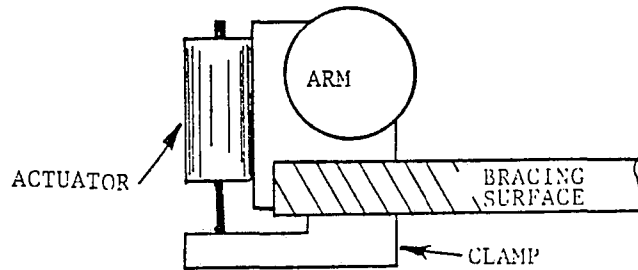


Fig. 3 Mechanical Clamping for Bracing

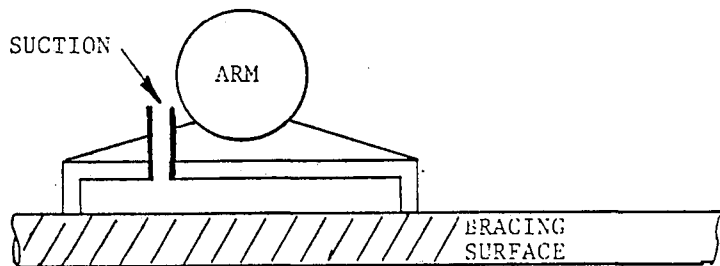


Fig. 4 A Vacuum Attachment for Bracing

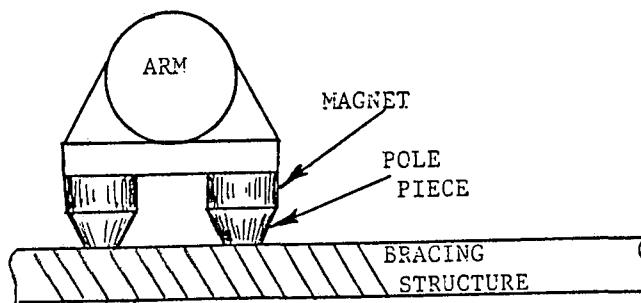


Fig. 5 A Magnetic Bracing Mechanism